INVESTIGATING EXTENT OF AN UNDERGROUND COAL MINE FIRE USING AIRBORNE INFRARED THERMOGRAPHY GEOREFERENCED TO LIDAR BASEMAP[1]

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Abstract. The Office of Surface Mining (OSM) has completed numerous abandoned mine land (AML) closures of coal-mine features in Cougar Mountain Regional Wildland Park just southeast of Bellevue, Washington. This park exists in an area with extensive coal mining (on seven coal seams) between the late 1860s to early 1950s. Several historical mine fires have been documented in the vicinity between 1890s and 1950s. The project site was originally observed to have venting steam in the early 1980s. In the late 1990s a linear band of fallen trees was observed in the area of the venting steam. In 2002, site investigations indicated that elevated ground temperatures corresponded with the No. 3 Seam crop line. Investigations in 2002 also recorded near-surface ground temperatures as high as 118 degrees Fahrenheit (ground temperature probe) at isolated locations near venting steam. Typical forest fuel ignition temperature is 302 degrees, so forest fire was not perceived to be an immediate risk. However, progress of the fire could lead to increased risk of ground subsidence and injury to park users. Typical ground temperatures measured with the probe were 10 to 30 degrees above ambient ground temperatures of around 50 degrees (at time of measurement). A hand-held infrared (IR) camera was also used to observe isolated areas of elevated ground temperatures.

After reviewing various investigation methods, it was decided to utilize airborne-georeferenced IR to establish a baseline ground temperature map to facilitate tracking the apparent underground mine fire. A helicopter gimbal-mounted IR camera, DGPS, and inertial navigation unit (INU) were utilized to georeference IR ground temperature data to a LiDAR based digital elevation model (DEM). The resulting ground temperature data overlaid onto the LiDAR topographic map was cross checked with ground locations and temperature targets. Airborne IR ground <u>surface</u> temperature readings and locations corresponded well to those on the ground, but, as expected, were lower than subsurface ground temperatures measured with a probe. Some small elevated temperature locations were obscured by vegetation, but the overall pattern of elevated ground temperature was more apparent utilizing the airborne IR data.

Additional Key Words: DEM, DGPS, ground temperature.

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Introduction

This paper is organized into the following sections.

- Project Summary;
- Project History and Background;
- Project Approach and Methods;
- Lessons Learned; and
- Conclusions and Recommendations.

Figures interspersed in the paper illustrate site information. Due to the format of this paper, not all figures were able to be included. Please refer to Hart Crowser 2003 and 2005 for additional information. Appendix A after the text presents additional useful IR background information.

Project Summary

Several "steam" vents apparently related to a burning underground coal seam have been observed by Park staff within Cougar Mountain Regional Wildland Park, near Newcastle, Washington (see Figure 1). The area was previously mined but not much is known about the extent of workings in the area of the fire (Hart Crowser 2003). One of the steam vents is located immediately adjacent to a main hiking trail/park maintenance road. The other, more extensive steam vent area (defined by an area of fallen trees including) is located within about 300 feet of this trail/road. Smaller foot trails reported in some hiking guide books also extend through this general area. The steam vents are in an area where several subsidence depressions exist that are related to abandoned mine workings.

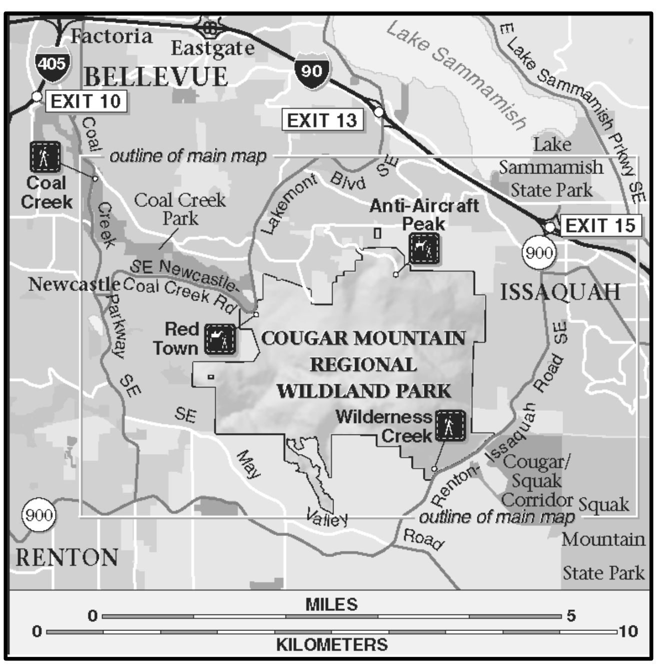

Figure 1. Vicinity Map

Selection of appropriate remedial measures for this site is complicated due to several factors. The site is within a County Park and the County desires to disturb the Park as little as possible to avoid damage to the Park and to avoid creating an attractive nuisance. Relatively few remedial measures other than excavation, quenching, and backfilling exist that would effectively abate all the potential hazards of this apparent underground mine fire. The excavate/quench/backfill option would disturb a significant amount of the park and likely have significant remedial costs. The unknown extent and severity of the apparent underground mine fire also complicate selection of appropriate remedial measures at this time. However, potential for off-trail users to fall into steep-sided subsidence pits, get burns due to sudden ground collapse, and be exposed to harmful gases are potential safety concerns. It does not appear highly likely that elevated ground temperatures would cause a forest fire based on our understanding of current conditions. However, sudden ground collapse (i.e., subsidence) resulting from the coal mine fire could lead to different conditions that could potentially start a forest fire. Thus, based on the available information it was determined to monitor the site and gain additional information until remedial measures appear warranted.

Background and Project History

Relatively little is known about the origin, development, or extent of coal seam or coal mine fires in Western Washington. According to the Bureau of Mines, most fires reported in coal mines or along outcrops arise through the action of people. However, there are reported instances in other parts of the country, where coal crop fires occur due to spontaneous combustion (related to exothermic oxidation of the coal) or other natural causes such as lightning strikes or forest fires. In the Newcastle area, the coal is typically covered by glacially derived soils more than 10 feet thick, and no outcrops were observed during our field reconnaissance. The coal seams in this area dip about 35 to 40 degrees below horizontal toward the north to northwest as shown on Figure 2. Accordingly, we surmise the steam vents are most likely the result of a fire in the abandoned mine workings.

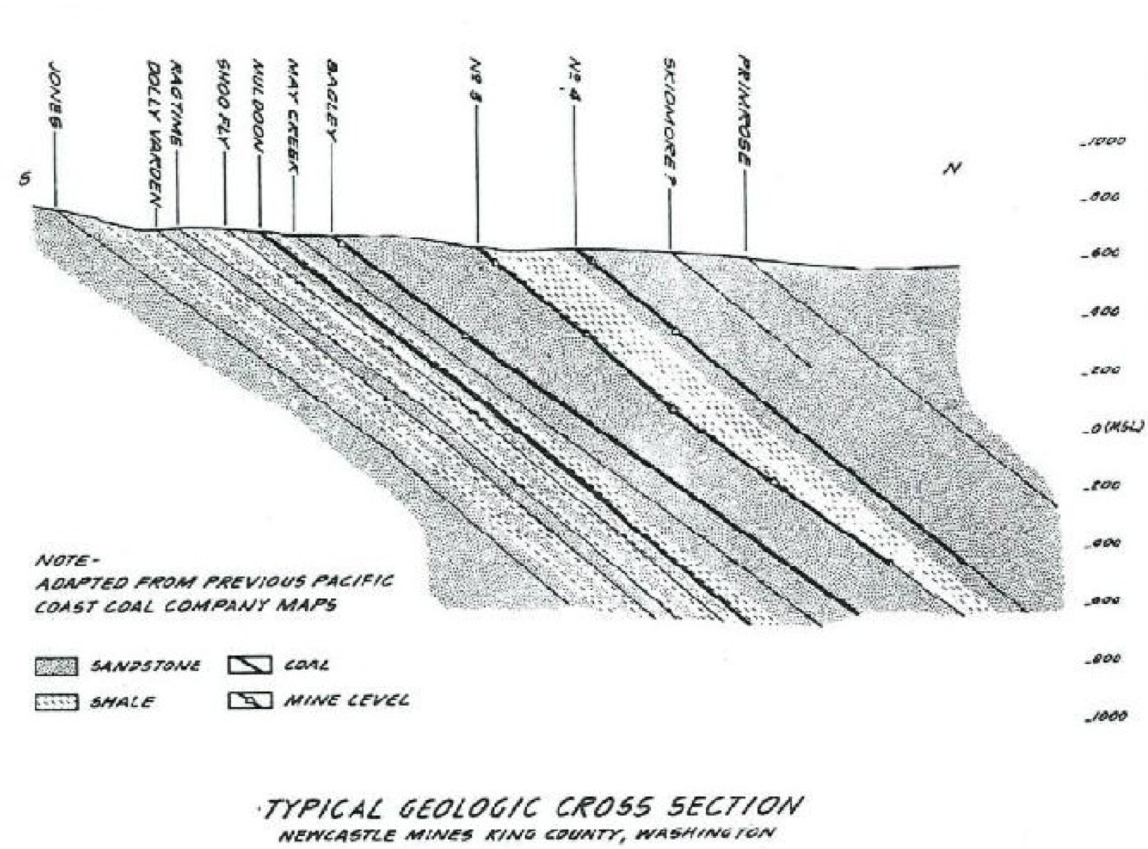

Figure 2. Typical Geologic Cross Section

Initial review of mine maps using an estimate of the steam vent location provided by King County Park staff appeared to indicate that the steam vents are related to a possible underground mine fire on the Bagley Seam. Location of a fire in the Bagley Seam is consistent with previous reports of mine or coal crop fires in the general vicinity. C. R. Dunrud's April 8, 1987, map indicates that there was a strip mine fire in the late 1940s and early 1950s, on the Bagley bed about 500 feet southwest of feature CC-340 (40-foot-diameter subsidence feature in main area of venting steam), and a 1945 underground coal mine fire in the Bagley Seam about 2,700 feet west of feature CC-340. Tim Walsh (Washington DNR, personal communication 2002) reported a fire in the Bagley Seam that was put out in the 1930s. However, the Bagley Seam workings are projected to be roughly 300 feet deep below the current steam vents, and the stratigraphic correlations along with GPS data collected by Hart Crowser (2003) indicate the apparent fire is more likely in the shallow portion of the No. 3 Seam, as depicted on Figure 3. McDonald and McDonald (1996) describe two fires further west on the No. 3 Seam in Section 26 (Township 24N, Range 5E) in the 1890s, and Ash (1921) indicates these were on the Second Level of the No. 3 Seam.

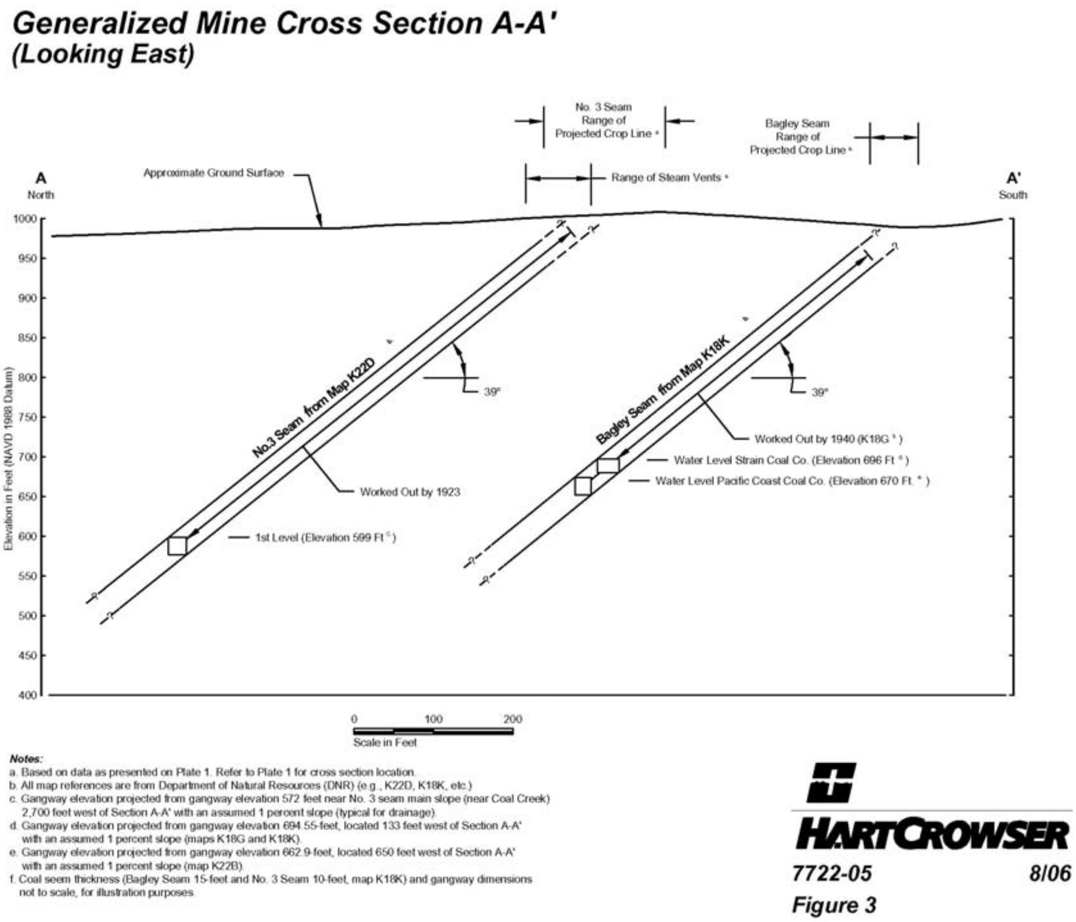

Figure 3. Generalized Mine Cross Section A-A’

Available mine maps do not have detailed information on the No. 3 Seam mine workings in the immediate vicinity of the steam vents. Mine workings on the No. 3 Seam below the steam vents are on the order of at least 50 to more than 100 years old. Analysis of other workings in the Newcastle area indicate such workings most likely have caved, but the caved debris may include remnant coal and other loose rock with interconnected voids that permits movement of air. Since the availability of fuel and oxygen is unknown, the extent of the fire and the potential for it to spread are also unknown.

We understand that OSM staff recall reports of minor steam venting in the area of CC-342 since the mid-1980s. King County Park staff observed steam venting from the ground at the locations described previously for the last several years, and described a linear feature of fallen trees (between 1996 and 1998) that may be related to high ground temperatures. The County Park staff also recollect anecdotal evidence of a dozer accidentally uncovering a mine fire in the vicinity of one subsidence feature in the 1950s. He indicated the associated smoke was reportedly observed as far away as Seattle.

At a brief site visit on March 27, 2002, with OSM and Park staff, we observed visible steam venting from several locations. The main location was a subsidence pit approximately 40 feet in diameter and more than 20 feet deep (Figure 4). Fallen trees and overturned tree stumps that had charred tree roots were also observed in the area.

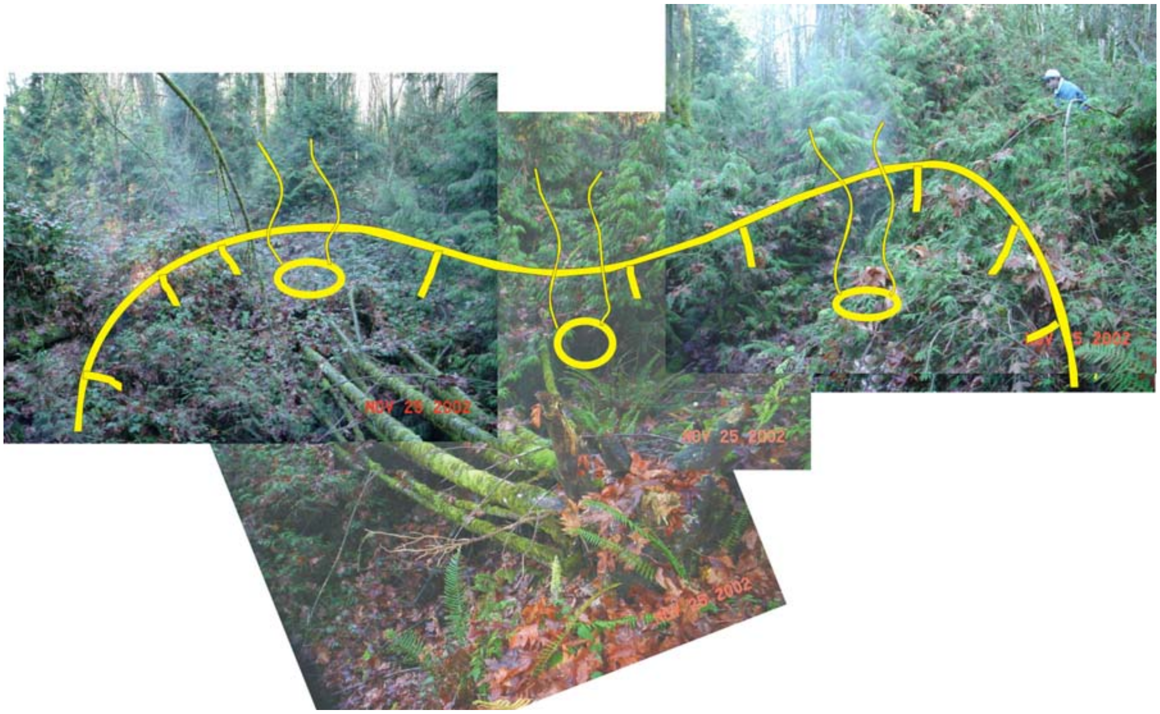

Figure 4. Typical Steam Vent in Subsidence Pit (Feature CC-340; yellow line shows approximate extent of subsidence and three steam vents)

<u>Project Approach/Methods</u>

The following sections describe the general approach and methods used for site investigation. We accomplished the following tasks in the general order indicated below.

<u>Prepare Initial Base Map Using LiDAR Based Topography</u>

Hart Crowser compiled a base map with topography generated from LiDAR data (x, y, and z data from the Puget Sound LiDAR Consortium [PSLC]) prior to inventorying AML features near or exhibiting venting steam. A portion of the completed map illustrating main area of elevated ground temperatures is included on Figure 5 (oversized figure attached).

A detailed description of LiDAR-generated topography is given in Hart Crowser (2003), but a basic description follows. LiDAR-generated topography is based on measuring the distance from an airplane to the ground surface by precisely timing the round-trip travel time of a brief pulse of laser light. Multiple reflections of the laser pulse off of vegetation and trees above the ground surface, as well as from the ground surface are recorded. The last recorded reflection is used to determine the distance from the plane to the ground surface below vegetation. Thus, LiDAR typically produces more accurate ground surface topography than traditional photogrammetric methods because it essentially "sees" through the tree cover. It also produces more detailed topography than traditional photogrammetric methods because of the higher density of points used to construct LiDAR topographic maps. The position of the airplane and direction of the laser pulse are measured using GPS and inertial navigation system (INS), as discussed in Hart Crowser (2003).

Typical absolute accuracy of the LiDAR elevation data reportedly ranges from less than 1 foot with little tree cover to less than 10 feet in heavily forested areas with tall (on the order of 60 to 100 feet tall) trees (see Hart Crowser [2003]). Comparison of LiDAR elevation (about 650 feet) and King County Park information at the Red Town Trailhead (640 feet) appears to support this absolute accuracy. Accuracy of spatial data (i.e., northings and eastings) is dependent on the accuracy of GPS and INS system components and their integration, but is typically between about 1 to 3 feet.

Information on the base map (Figure 5) is from the followings sources:

- Township, range, and section data were obtained from the Washington State Geospatial Data Archives (www.wagda.lib.washington.edu/data/plss.html);
- Northing and Easting data were provided with the LiDAR data from PSLC;
- King County trail information was provided by the King County GIS Center and the trails shown have been located by GPS; and
- Abandoned Mine Land (AML) features were located by Hart Crowser with differentially corrected GPS, or DGPS.

Other information on the base map was obtained as indicated on the map.

Field Locate and Inventory Features near and with Venting Steam

Initially known and new AML features near areas with venting steam were field located and briefly inventoried. This was done to more accurately delineate the coal seam crop lines stratigraphically above and below the area where the steam vents were observed. After these field data were gathered, GPS locations were differentially corrected and plotted on the base map (Figure 5).

After incorporating data from our field observations near the steam vents onto the base map, we inventoried features with venting steam generally along the same coal seam. Figure 5 illustrates features where steam was observed venting from the ground (CC-334, CC-335, CC-336, CC-338, CC-339, CC-340, CC-342, CC-351, CC-352, CC-353, and CC-354). The main location where steam vents were observed was between CC-340 and CC-334. This area coincides with a linear swath of fallen trees that is about 40 feet wide by about 200 feet long.

Field Investigation Findings Prior to IR Survey

Location of Venting Steam. The observed steam vents are located roughly parallel to the projected No. 3 Seam crop line (location where the projected coal seam would intersect the ground surface). The steam vents are located about 50 feet north to northeast of the No. 3 Seam crop line projected by Dunrud (see Figure 2). At this location, the depth of the No. 3 Seam (and potential fire) is estimated to be about 40 feet since the coal beds dip toward the north to northeast at about 38 to 40 degrees below horizontal in this area. The depth of the fire could be much deeper if the fire extends down the dip of the coal seam or if the fire is burning in a lower seam.

The two distinct areas of steam vents that we have observed could be separate areas of combustion, or separate surface expressions of a single fire within the underground coal seam. The degree of hazard to Park users and staff is unknown, but may be significant. Potential hazards due to ongoing combustion include sudden subsidence, high temperatures and/or noxious fumes at the surface, and the potential for forest fires.

Possible Coal-Mine Fire Extent. Similar to any fire, coal mine fires are limited by fuel, oxygen (air), and an ignition source. The fuel (coal) and oxygen define the fire's spatial extent. Coal in the No. 3 Seam occurs as an inclined plane with a thickness of about 10 feet, which intersects the ground surface at its top (projected outcrop) and dips underground to the northeast. Thus, the fire in this coal seam can only burn to its upper extent (i.e., the subcrop) toward the southwest or laterally as the subcrop north of the projected outcrop trends cross country toward the northwest and southeast. Since the thickness of overburden at the site is unknown, the distance between the subcrop and project outcrop is indeterminate, but likely on the order of a few tens of feet in this area. Groundwater limits the air supply to the coal seam fire and limits the northeastern extent of the fire. Based on available information on the No. 3 Seam, the area available for combustion is limited to a band about 500 to 650 feet wide extending northeast of the No. 3 Seam crop line projection shown on Figure 5. The coal seam extends laterally (northwest to southeast direction) a great length. While it could burn considerable distances in these two directions, evidence to date indicates combustion is limited to a zone about 700 feet in length, plus some outlying "hot spots" that may or may not be part of the same fire(s), as discussed herein.

An airshaft is reported to exist between CC-335 and CC-340 (Figure 5). This is important because it could connect different coal seams and provide an additional air source, and/or potentially allow a coal-mine fire to spread between two different coal seams. The airshaft location was transferred from a poor quality 1895 mine map to Figure 5 by scaling from the nearest section corner; thus, the location is approximate. A King Co. Parks staff member, recalled that someone looked for the airshaft with a dozer in late 1970s, without finding it. See Hart Crowser (2003) for additional discussion of potential air sources.

Elevated Ground Temperatures. In November 2002 a ground temperature profile was measured to determine temperature variation across the coal seam crop line shown on Figure 5. The profile (T1 - T2, see Figure 6) was oriented perpendicular to the swath of fallen trees, which is approximately perpendicular to the No. 3 Seam crop line. The temperature was measured at about 10-foot spacing along the profile using 6-inch-long metal temperature probes inserted full length into the ground and allowed to stabilize. Baseline/reference air and ground temperatures of about 40 and 50 degrees Fahrenheit, respectively, were taken about 200 feet away from the steam vents.

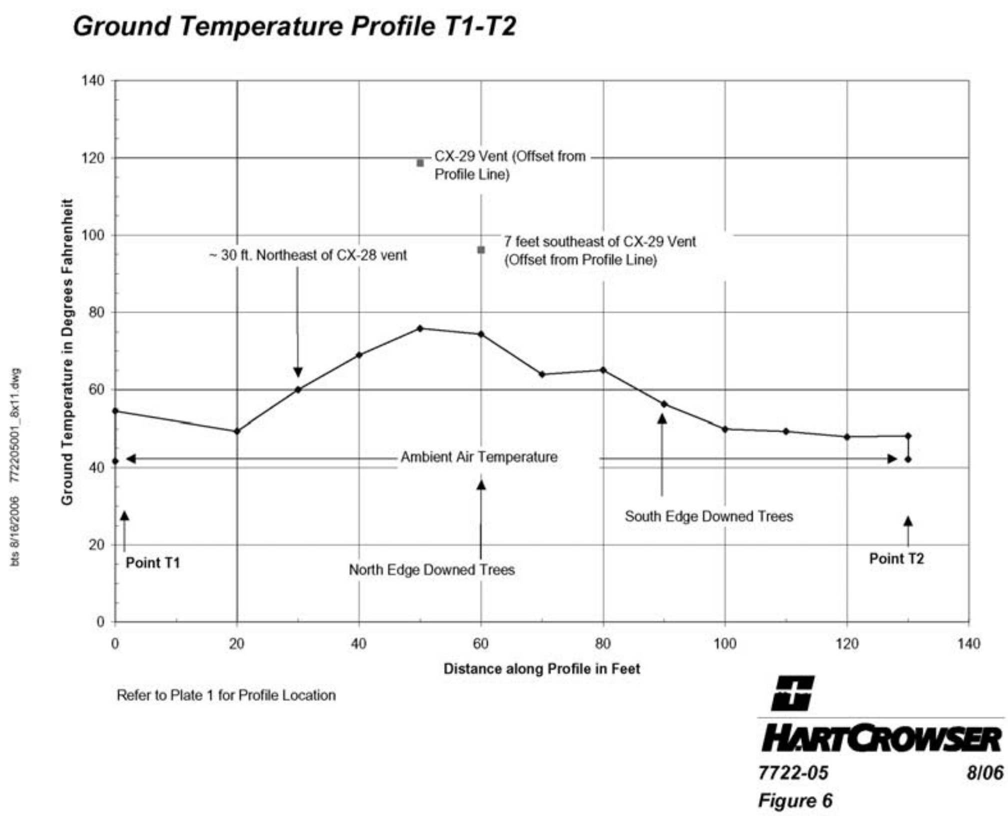

Figure 6. Ground Temperature Profile T1 – T2

Figure 6 illustrates elevated ground temperatures up to about 76 degrees Fahrenheit along the temperature profile, which was about 30 to 50 feet away from steam vents CC-338, CC-339, and CC-340. A ground temperature of 118 degrees was measured at steam vent CC-339 (11/25/02 and 1/25/06). We speculate that the elevated near-surface ground temperatures may be high enough in some areas to kill the tree roots, as indicated by the swath of fallen trees noted above. Figure 5 depicts vents within an area about 400 feet long, which suggests the extent of the fire is larger than indicated by the fallen trees.

We observed tree roots that had oxidized to charcoal in the general vicinity of the temperature transect, which suggests ground temperatures could be, or have been, higher than our measurements. However, we understand from King County Park staff that forest fires have historically occurred throughout the general area and charred wood material could have resulted from such fires.

At a meeting with OSM and King County, Kristi McClelland (King County forester with 25 years prior experience with Washington Department of Natural Resources) indicated that typical ignition temperatures for forest fuel is about 302 degrees Fahrenheit in a confined environment with buildup of gases (Café 2004 and Babrauskas 2003). She also indicated that sustained temperatures higher than 248 degrees Fahrenheit (Café 2004 and Babrauskas 2003) would be required to char tree roots. Kristi indicated that the area of downed trees between features CC-340 and CC-336 did not have a lot of highly flammable surface fuel (i.e., conifer litter) that typically is necessary to support rapid spread of forest fires.

IR Ground Surface Temperature Detection Methods and Results

The intent of this work was to define a baseline for spatial distribution of elevated ground temperatures on the day of the IR flight (February 4, 2005, between about 2 and 3 p.m.). This section summarizes the IR methods used to detect elevated ground surface temperatures and presents results of the IR investigation.

IR Temperature Detection Basics. IR temperature detection involves measurement of emitted electromagnetic radiation (heat energy in the infrared wavelength range of about 2 to 14 µm). For comparison, the visible wavelength is about 0.3 to 0.7 µm. IR radiation measurements are converted into temperatures using a series of equations and assumed conditions (see Appendix A and http://www.myfirecommunity.net/documents/ Infrared_Field_Guide.pdf for a more detailed description). The main factors affecting detection of emitted heat energy are the size of the heat source; the distance from the IR sensor to the heat source; whether the heat source is obscured from the IR sensor (i.e., emitted heat energy is blocked by vegetation, and/or absorbed by significant water vapor or dust in the air); and the emissivity (material property indicating how well the material emits heat energy).

IR Temperature Detection and Mapping Methods. A helicopter equipped with an IR camera was used to measure and map the spatial distribution of elevated ground temperatures at the site. Hart Crowser used the following general process to accomplish our work.

- Utilized LiDAR based topography map created during prior investigation work.

- Selected an IR subconsultant that could perform the following IR survey requirements:
  - Produce a georeferenced IR <u>image</u> of the elevated ground surface temperature <u>areas</u> and overlay this onto the existing LiDAR GIS (ArcView) base map;
  - Confirm specified flight coverage (using GPS waypoints) and altitude during flight using real-time GPS of targeted area via on screen display;
  - View IR information and video image real-time during flight to allow immediate feedback of information collected;
  - Calibrate IR camera with temperature control "targets" on the ground; and
  - Cross-check georeferencing accuracy with GPS benchmarks on the ground.
- Hart Crowser coordinated the IR flight with subconsultant including pre-flight site visit, discussed georeferencing benchmarks, and ground temperature calibration sources. We arranged to fly an IR survey in the winter when most tree leaves are off to optimize detection of small temperature sources. We attempted to fly the IR survey in the early morning when temperature contrast was best, but rainy weather conditions necessitated an afternoon flight (overcast all day). Hart Crowser flew along with the subconsultant on the IR survey.
- Subconsultant confirmed IR flight results on the ground after the flight with hand-held IR camera and/or temperature probes.
- Subconsultant georeferenced IR data.
- Subconsultant provided IR data layer to overlay on original LiDAR base map.
- We reviewed subconsultant's final product, modified the IR data layer and overlaid it on the LiDAR base map, documented IR flight information for reliable repetition in the future, and documented lessons learned to improve future performance.

Fireball Information Technologies (hereafter referred to as Fireball IT, selected IR subconsultant) used the following specific equipment and methods to achieve the required information for this project. See Appendix A and www.fireballit.com for more detailed information.

- Fireball's IR camera was gimbal (articulates in all directions) mounted on a Bell 206 Jet Ranger helicopter operated by Redding Air Service.
- Fireball's positioning system utilized the helicopter's DGPS and altimeter, an inertial navigation unit (INU, measures/records azimuth and inclination camera is pointing), and the existing LiDAR digital elevation model (DEM) to overlay the IR camera temperature information onto the base map. The IR information was georeferenced (visual data are given coordinates) and orthorectified (stretched and skewed to match actual terrain) so that the IR temperature data are correctly located on the base map.

- Fireball flew over the temperature calibration targets at nearly the same altitude (300 feet over entire area and 100 feet over main area between CC-342 and CC-337) as during the IR survey to optimize the IR camera calibration.
- Fireball flew over elevated temperature areas with overlapping flight paths using different camera angles to minimize the amount of vegetation obscuring temperature sources.
- Fireball confirmed IR flight results on ground after flight with hand-held IR camera and/or thermocouples.
- Fireball assumed an emissivity of about 0.97 for water bath temperature calibration targets and wet ground conditions.
- No correction for atmospheric moisture content was considered for two reasons. First, calibration was done in the same conditions. Second, atmospheric moisture would have to be significant (i.e., fog) to affect the results for the low altitudes flown with the low wavelength range (2 to 5 μm) of the IR camera.

<u>IR Survey Results</u>. This section summarizes the results of the IR elevated temperature data. Figure 5 is a close up/more detailed map of the main area of venting steam. Figures 4 and 5 indicate other isolated areas with temperatures above the background ambient ground temperatures (43 and 46 degrees Fahrenheit in different areas on Figure 6). Figure 6 illustrates elevated temperatures of vehicles (e.g., warm engines) in the Red Town Gate parking area. Note that Figures 2, 4, and 5 and Table 2 indicate areas with apparent elevated temperatures near the background temperature that would be good to monitor to determine whether temperatures increase (see Conclusions and Recommendations section).

The following list summarizes the main findings from the IR elevated temperature information illustrated on the aforementioned figures.

- Areas of elevated ground surface temperature were generally the same as what has been previously observed or reported. However, some areas of elevated temperature were noted to extend farther than visual observations indicated (especially west of CC-340).
- The pattern of elevated temperatures follows the projection of the No. 3 Seam outcrop line as our prior investigation suggested. The IR survey indicates that some areas with elevated temperatures (> 61 degrees Fahrenheit, potential "hot spots") exist further west than shown on Figure 5. Initially it was not known whether these potential "hot spots" were related to an underground mine fire, related to the main combustion area shown on Figure 5, and/or were anomalous elevated temperature readings (animals, people, man-made material/debris, etc.). However, a field visit on January 25, 2006, with a hand-held IR camera and a 3-foot-long temperature probe did not reveal elevated ground temperatures significantly higher than background

temperatures at the potential "hot spot" locations (GPS coordinates digitized from LiDAR base map).

- Some areas with known elevated temperatures and/or steam vents (CC-338 and CC-339) were not detected with the airborne IR survey due to the size of the heat source and being underneath a significant amount of vegetation/trees.

- Maximum ground surface temperatures detected from the airborne IR survey were less than about 80 degrees Fahrenheit. Airborne IR survey temperatures are expected to be less than actual ground temperatures because the airborne IR survey detects ground <u>surface</u> temperatures and not subsurface ground temperatures. Thus, temperatures measured with a thermometer probe stuck <u>into</u> the ground or a hand-held IR camera <u>close</u> to the heat source should yield temperatures higher than those from the airborne IR surveys because they are closer to the heat source and have a more unobstructed view.

  For comparison, the highest ground temperature we observed was 118 degrees Fahrenheit measured with a 6-inch-long thermometer in the ground near vent CC-339 under vegetation (November 2002). The highest temperature measurement with OSM's hand-held radiometric IR camera (FLIR ThermaCAM E-Series) was 108 degrees Fahrenheit for a warm boulder in the side wall of a subsidence (January 2004). We have measured a ground temperature of 75 degrees Fahrenheit with a 6-inch-long temperature probe at the same location that OSM's hand-held IR camera measured 67 degrees Fahrenheit. This information suggests that vegetation obstructing heat sources, the distance from the heat source, and other factors (see Appendix A) could cause measurements of actual ground temperatures to be on the order of 10 degrees higher than airborne IR survey temperatures (7 to 10 percent higher per Zajkowski, Queen, VanBurren 2003).

<u>**Lessons Learned**</u>

This section presents lessons we learned while performing this work. We present this information here to aid in obtaining repeatable results for future work at this site and to improve performance/efficiency of such work.

<u>IR Investigation Lessons Learned</u>

The following list indicates lessons we learned. Lessons learned as reported by Fireball IT are provided in Appendix A.

- Our initial search for IR flight subconsultants yielded few options. Initially one IR flight subconsultant was selected to perform an initial IR flight in March 2004. However, they were not able to produce the georeferenced IR image mapping specified, despite example work products that appeared to produce such maps. Thus, a second IR subconsultant was selected based on a review of vendors listed in the U.S. Forest Service's Infrared Field Users' Guide and Vendor Listings (Zajkowski, Queen, VanBurren 2003). This guide indicated that both IR subconsultants we worked with could georeference <u>IR</u>

data (temperature at discrete points or temperature areas). However, we learned that only Fireball IT could georeference the IR images (temperature areas). Therefore, it is critical to confirm that the IR subconsultants satisfy the requirements specified in the IR Temperature Detection and Mapping Methods section.

- A preliminary flight over the site to obtain high altitude aerial photo, georeferencing information, and calibration of the IR camera would have made the IR subconsultant's work more efficient as discussed in Appendix A.
- The ideal time for the IR flight is on a clear winter day so that the temperature contrast is greatest, leaves are off most trees (optimal time is typically December through early February at this site), and there is minimal atmospheric moisture to interfere with detecting elevated ground surface temperatures. Scheduling a good weather day in the winter is problematic for this site. A one week window should be allowed, and the IR subconsultant should make the final decision on flight date since they best know the limitations of their equipment.
- Laying out benchmarks with known GPS coordinates that are visible from the air prior to the flight would have aided georeferencing the IR images and confirming its accuracy. This was attempted by Fireball, but their hand-held GPS did not have good reception in the forest. We would recommend doing this with a GPS and antenna on a range pole about 15 feet above the ground surface (similar to what Hart Crowser uses for OSM work). We recommend that future work use the GPS benchmark coordinates in Table 2. These points should be made visible from the air for the day of future IR flights and their accuracy should be confirmed by surveying.
- Fireball Information Technologies' automatic georeferencing system (accurate to less than 10 feet) malfunctioned the day of the flight (see Appendix A), which required IR imagery to be manually georeferenced using the LiDAR base map. Discussions with the IR subconsultant indicated the manual georeferencing produced an accuracy of about 10 to 30 feet.
- File sizes for some of the IR and video data were enormous (largest file was 14 GB), which necessitated transferring data via a portable external hard drive (approximately $100).
- A higher quality video camera during the IR flight would aid recognition of ground features, but is not critical for this work.
- Note that revised GPS coordinates for specific features were collected. These GPS coordinates were collected with the antenna on a 15-foot-high range pole to attempt to collect more accurate positions for features from our initial investigation that did not appear to match up with field sketches and LiDAR subsidence features. Some of the new GPS positions still do not match up with LiDAR features. Note that the GPS positions are only as accurate as the method allows given forest conditions and satellite configurations at the time positions were collected. Based on our experience, GPS positions in this area

are typically accurate to about 50 feet, but can be more (as much as about 100 feet) or less depending on specific conditions.

IR Detection and Typical OSM Coal-Mine Fire Reclamation Costs

In this section we present the costs for this IR investigation work as well as typical coal-mine fire reclamation costs from other OSM projects.

Cougar Mountain IR Investigation Costs**.** The costs for this project consist of the IR subconsultant's costs and Hart Crowser's costs. The IR investigation costs are a function of helicopter unit rate and flight time (helicopter requires special FAA approval and was from Redding, CA), as well as the subconsultant's field and analyses costs. For this job the total subconsultant cost was about $14,000. Current helicopter costs are about $1,000 per hour (Jet Ranger/Bell 206) and Fireball IT daily costs are about $5,000 (day of flight and typical post processing).

Hart Crowser's effort included researching the detection method, selecting the IR subconsultant, coordinating the flight with IR subconsultant and King County Park staff, assisting with IR flight, reviewing results, incorporating IR imagery onto our LiDAR base map, and documenting the findings in this report. Our cost for this work was about $27,000.

Typical Coal-Mine Fire Reclamation Costs. On occasion, OSM has attempted to extinguish coal seam or coal mine waste pile fires by earthwork to cover fire areas to prevent air from supporting combustion, and by excavation to cut off a burning area from extending further along a coal seam. Either approach requires extensive land disturbance in the immediate vicinity and work support areas for access and staging. In many cases, the initial work is not successful and extinguishing the underground fire requires two or more stages of work. The following typical coal-mine fire reclamation costs are presented for information purposes only.

A variety of site-specific factors affects the actual reclamation costs. These costs are from OSM projects in various other states where OSM determined that the reclamation was necessary for safety considering location of the fire, land use, and other reasons. OSM coal mine fire reclamation facts and typical costs for projects (mostly in the eastern U.S.) between 2002 and 2004 are as follows:

- Reclamation areas between 0 and 10 acres (not all area necessarily associated with mine fire);
- Volume of material involved was 150 to 30,000 cubic yards;
- Unit project costs ranging range up to $183,000 per acre with an average of $43,000 per acre (calculated by dividing total cost by reclamation area).

Conclusions and Recommendations

In this section we present conclusions from our work and provide recommendations for activities at the site. The following list presents potential safety concerns, monitoring recommendations, recommendations for future work at the site, and other general recommendations.

- OSM provided reports from this work (Hart Crowser 2003 and 2005) to King County Department of Natural Resources and Parks, and is available to consult with them as necessary to answer questions regarding the areas of potential hazard.
- The venting steam is an attractive nuisance because it is interesting to potential onlookers. Current recreational users of the park, especially orienteering or other off-trail users are at risk of falling as subsidence pits develop or expand in the fire area. Potential for getting burns due to sudden ground collapse, and possible exposure to harmful gases are related potential safety concerns. There is no way to predict risk of subsidence or ground collapse in areas of the fire except by drilling at discrete locations and it is difficult to extrapolate conditions from one location to another.
- Elevated temperature areas are not necessarily visible by eye and/or may be obscured by heavy vegetation, fallen trees, etc (see Figures 7 and 8). Care should be taken by anyone who must approach areas with known elevated ground temperatures or previously observed steam vents. We recommended that Park workers not approach such areas alone for safety reasons. We also recommend that people enter such areas from the southwest to avoid walking over shallow portions of the coal seam, which would be where ground collapse would be most likely.

Figure 7. Typical park vegetation in area of steam vent.

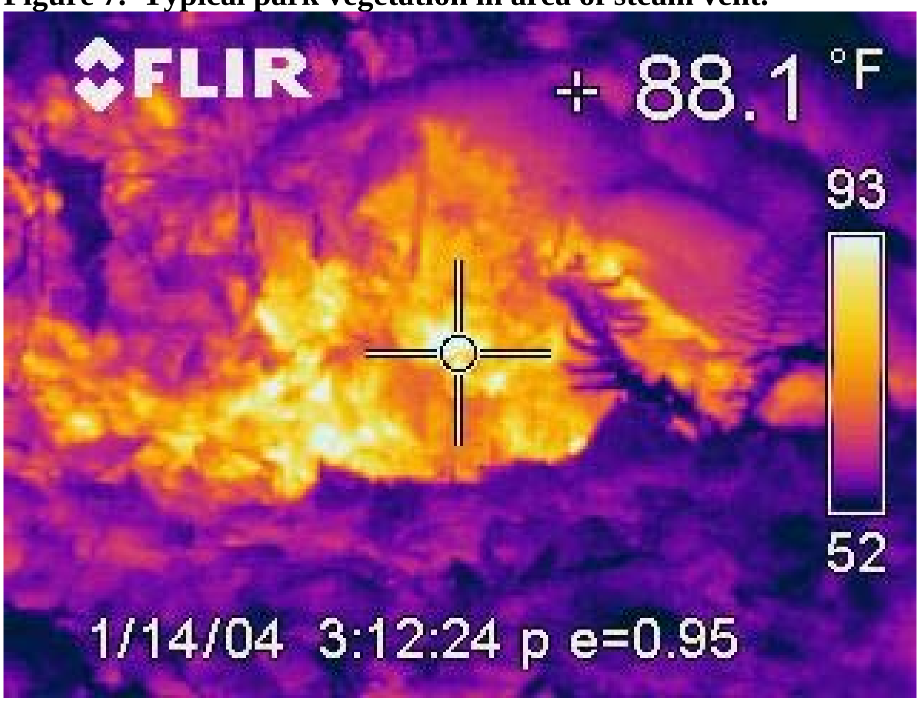

Figure 8. Same area as Figure 7 viewed through a temperature sensing IR camera indicates the temperature extremes associated with this vent feature.

- Based on available information, it does not appear highly likely that elevated ground temperatures would cause a forest fire based on our understanding of current conditions, generally wet climate, lack of highly flammable forest fuel, measured ground temperatures below 120 degrees Fahrenheit, and an ignition temperature for wood of around 300 degrees Fahrenheit (see Project Summary section). However, changes in the fire should be monitored over time, and sudden ground collapse (i.e., subsidence) resulting from the coal mine fire could lead to different conditions that could potentially start a forest fire. Thus, caution should be used in addressing this situation.

King County has performed some limited forest fuel cleanup around the perimeter of areas with elevated ground temperatures as a precautionary step. Additional forest fuel cleanup may be necessary to be effective. However, we understand disturbing the Park as little as possible is desired to avoid damage to the Park and to avoid creating an attractive nuisance. It may not be safe to work with heavy equipment within such areas due to the potential for sudden ground collapse, and ground crews should also take necessary precautions.

- King County has developed a monitoring plan and is implementing it to assess changes in risk related to subsidence or steam vents (new or extended) at critical areas. Current Elevated Temperature Points (airborne IR temperatures of 61 degrees Fahrenheit or greater) and Additional Monitoring Points (temperatures just above background temperatures of 43 to 46 degrees Fahrenheit) were included in Hart Crowser (2005). We recommended that the aforementioned elevated temperature points (see next major bullet) be monitored. The following items were also recommended to be included in the monitoring program:

  - Visual observations and photos from consistent points and in the same direction;
  - Note indications of ground instability (e.g., tension cracks, vegetation distress, settlement, etc.) around subsidence pits or formation of new ones;
  - Note new and former areas of venting steam;
  - If ground temperature readings are taken and recorded, establish consistent locations and depths for these measurements; and
  - Note other items, such as areas of fallen trees, that may indicate a change in the shape or form of the underground coal mine fire.

- The Additional Monitoring Points have temperatures slightly above background temperatures (based on airborne IR survey) and are in line with the coal-mine features. These elevated temperature points could not be dismissed as being erroneous due to solar heating of an exposed rock, animals, humans, etc., and thus were preserved until additional monitoring could be performed. We recommend that Additional Monitoring Points be observed initially and ground temperatures measured (with hand-held IR camera) to determine whether these points should be included in ongoing monitoring.

- King County has also taken steps to provide additional signage, public education, and public communication of potential mine hazards that exist in the Park. We understand King County has/is working with emergency responders (e.g., fire department, etc.) to educate them of the potential hazards in this area.

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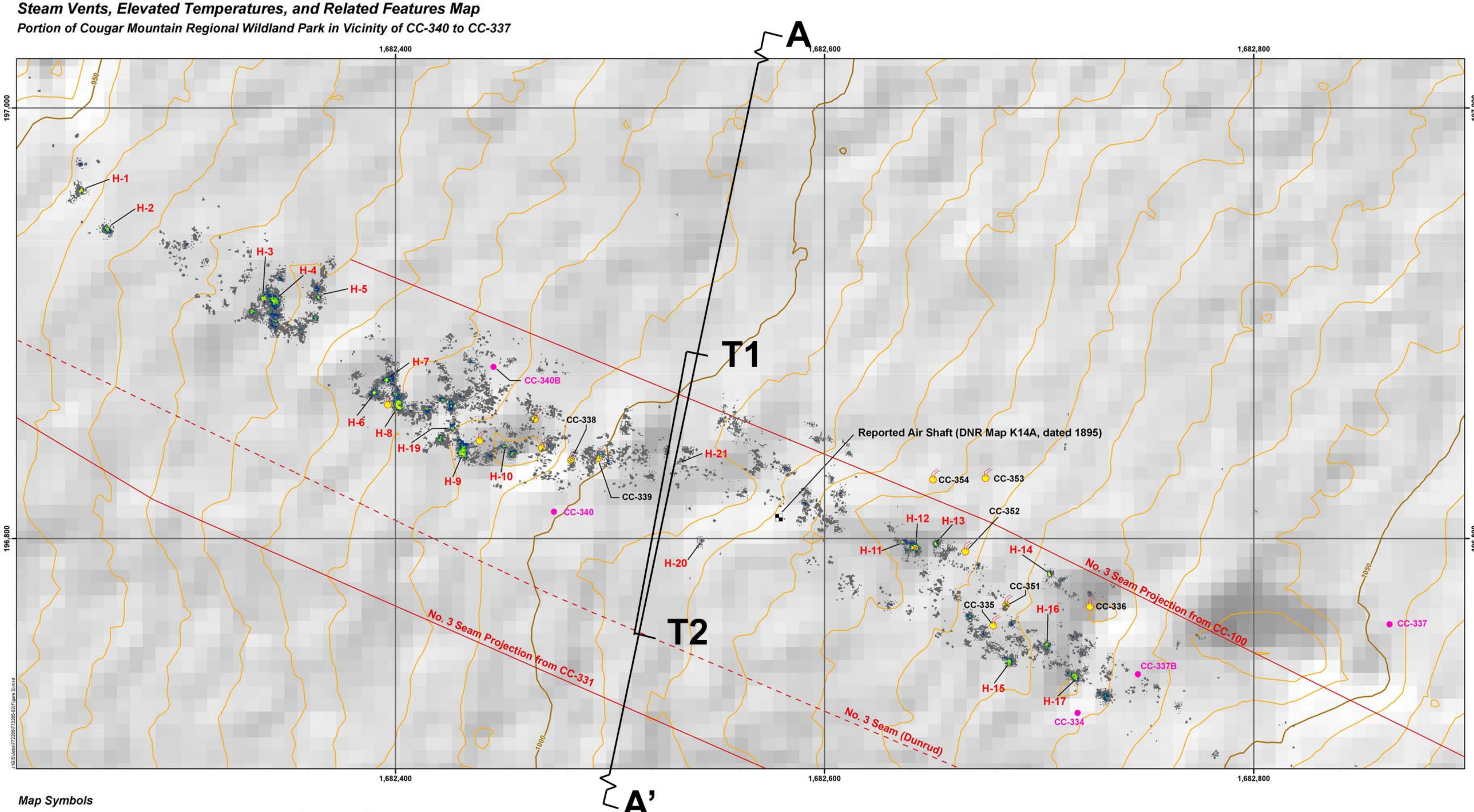
Steam Vents, Elevated Temperatures, and Related Features Map

Portion of Cougar Mountain Regional Wildland Park in Vicinity of CC-340 to CC-337



Map Symbols

- CC-340 ● New Non-Reclaimed AML Feature Location[1] and Number[3]
- CC-335 Steam Vent Location[1] and Number[3]
- 1,682,000 Washington State Plane Coordinates[5]
- Reported Air Shaft
- King County Cougar Mountain Public Trails[6]
- H-18 Hot Spot with Temperature Greater Than 61 Degrees Fahrenheit Location and Number

Maximum Elevated Temperature Detected in Degrees Fahrenheit[9] (Northeast of Upper Cave Hole Trail)

- 43 - 50
- 50 - 55
- 55 - 61
- 61 - 66
- 66 - 72
- 72 - 77

0 15 30 60

Scale in Feet

N

Note:

See Figure 2 for all legend items and notes.

HARTCROWSER

7722-05 *10/05*

Figure 5

APPENDIX A – ADDITIONAL INFRARED INFORMATION

By J. Timothy Ball, Ph. D, President of Fireball Information Technologies, LLC

A Brief Introduction to Infrared Temperature Measurements in Relation to Practical Understanding of Underground Fire Activity and Extent

The first step toward an understanding of thermal (often called blackbody) radiation is to describe the relationships between temperature, wavelength, and energy emitted by an ideal thermal radiator (blackbody). It is well known that objects at different temperatures emit radiation (heat energy) of different wavelengths or colors. For example, the wires in a heater begin to glow red when heated and the blue part of a candle flame is hotter than the yellow portion.

Both the total quantity of radiation emitted by an object and the distribution of that radiation across the wavelength of the spectrum vary with the temperature of the object. This radiation can have a peak energy distribution in the infrared, visible, or ultraviolet region of the electromagnetic spectrum. The hotter the emitter, the more energy emitted and the shorter the wavelength. An object at room temperature has its peak radiation in the infrared while the sun has its peak in the visible region.

Quantity of Radiation Varies with Temperature

The energy radiated per unit surface area of a "*perfect blackbody*" object is a function of the fourth power of the objects temperature T, as described by the Stefan-Boltzmann law

$$W_s = \sigma_s T^4 \text{ watts/m}^2$$

where σ_s = 5.67 x10^8 watts/m$^2\cdot$K^4 (Stefan-Boltzmann constant),
T = Temperature (K), and
W_s, = power per unit area called the emitted radiant flux density.

A graybody is an object that does not emit as a perfect "blackbody" but at a fraction of the theoretical maximum of a blackbody. The blackbody's emitted radiant flux density is reduced by a factor called the emissivity. The emissivity (ε) is dependent on the material emitting and is less than 1. For a graybody the emitted radiant flux density is:

$$W_s = \varepsilon\, \sigma_s T^4 \text{ watts/m}^2$$

Very few substances have emissivities of 1, although there are some simple tricks that one can use to construct cavities in objects that act as near perfect blackbodies.

Spectral Distribution of Radiation Varies with Temperature

The radiation emitted by gray or black bodies is not emitted at a single wavelength (color) rather the radiation is distributed over a broad spectrum of wavelengths. Planck's Radiation Formula, which describes the spectral distribution of energy as a function of temperature, looks daunting but what it describes is easy to understand and appreciate. So skip this formula if you want and go down to the following graph.

The quantity of energy emitted in any waveband (set of adjacent wavelengths, $\Delta\lambda$, between λ and $\lambda + \Delta\lambda$) is the spectral flux density W_λ multiplied by the size of the waveband, $\Delta\lambda$. In 1900, Max Planck announced the following formula that fit experimental measurements of W_λ. The formula bothered him so much that later that same year he realized that equation could only work if light came in quantized packets. That realization sparked the abandonment of Newtonian Mechanics in favor of Quantum Mechanics, Einstein followed and we common thinkers have been scratching our heads ever since.

$$W_\lambda = \frac{C_1}{\lambda^5} \frac{1}{e^{\frac{C_2}{\lambda T}} - 1}$$

Where:
$C_1 = 2\pi hc^2$
h = Plank's constant
c = speed of light
$C_2 = hc/k$
k = Boltzman constant
T = Temperature in degrees Kelvin
λ = wavelength

The spectral flux density from Planck's formula is plotted for five temperatures on the following figure. The wavelengths are plotted in units of microns. Notice that the axes are logarithmic. The visible spectrum and the waveband in which typical shortwave and longwave infrared sensors/cameras operate are shown for reference.

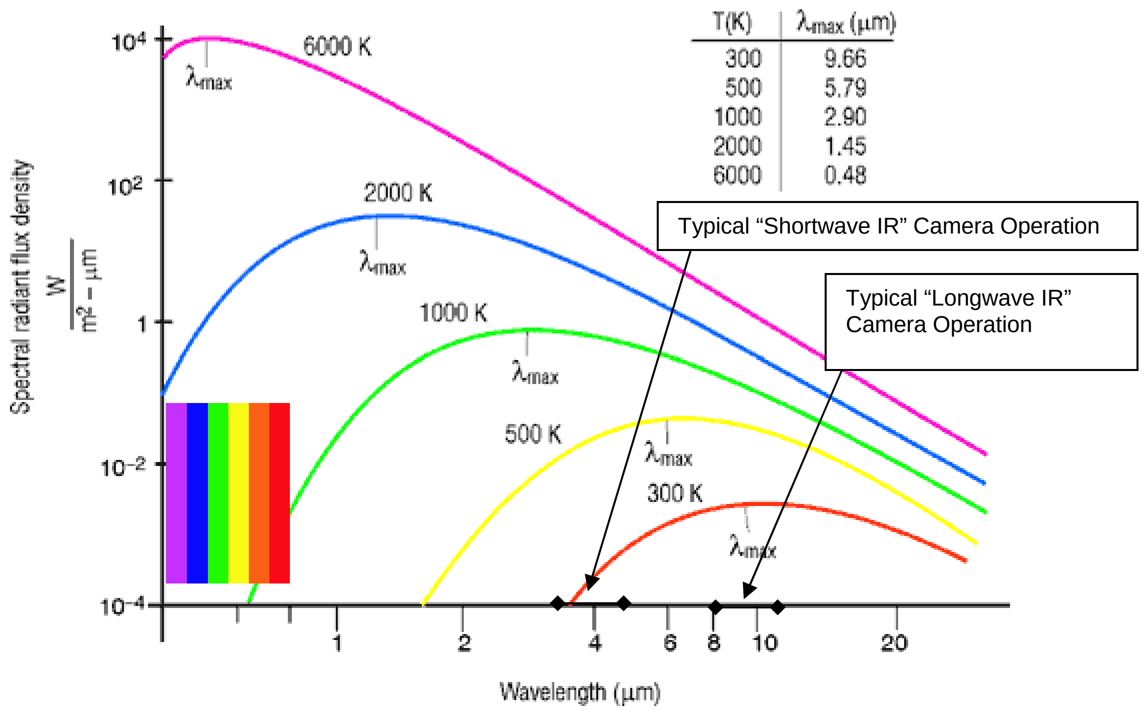


Figure A-1. Spectral radiant blackbody flux density distributions at various temperatures (visible spectrum range is up to about 0.7µm)

Single waveband (short- or long-wave) IR sensors report either the photon flux or energy flux in small pieces of the overall spectrum. Looking at those small wavebands in relationship to the family of curves suggests that there is a problem in trying to measure temperature with such sensors. The problem is, how can one tell the difference in temperature between an object at say 300K from an object at 500K but that is 100th the size (or 10 times farther away, because the amount of radiation declines as the square of the distance from point sources) because both object would show roughly the same amount of energy (or of photons) to the sensor. The answer is, you can't unequivocally tell the difference. All single wavelength radiation sensors will have this problem.

Consideration of the spectral distribution of radiation graph above does suggest that using two or more rather than one waveband for measurement can be used to definitively measure temperature. While this is true, instruments that simultaneously measure multiple wavelengths from airborne platforms (generally in the form of line scanners) are complex, costly, don't work well for low flying aircraft, and do not produce framed image output directly.

<u>Practical Field Measurements of Temperature</u>

In practical field measurements both the size and the distance from an object can significantly alter the temperature registered by a sensor. The closer one is to an object the hotter it will tend to appear because more radiation reaches the sensor as well as the fact that sensors elements (pixels) tend to "see" (collect energy from) less of a mixture of hot and cold areas.

This latter, "pixel mixing" issue is clearly worse where the physical structure of the terrain and vegetation are complex as they are at Cougar Mountain. In all likelihood, one can find small areas at higher temperature than is indicated by our color-coded temperature scale right at the opening of active steam vents because our pixels are bigger (including slightly cooler areas) than many of 2- to 4-inch-diameter openings. This situation is illustrated by the fact that one can put a thermocouple in or point a hand-held radiative thermometer down a steam vent and record a temperature of perhaps 35 C while the surface right at the throat of the vent might be only 25 C. Temperature can vary a great deal over small distances for objects with low thermal conductive capacity.

One manifestation of the radiation sensor picture element "seeing" a mixture of temperatures is the fact that some known steam vents were not detected in the survey. Heat sources have to be large enough to "counter" the cold surface temperature if the source is to be detectable above background noise. Another, somewhat related way that heat sources were almost certainly missed in this aerial survey occurred when the steam vent and heated surrounding was completely obscured by fallen tree trunks. During ground-truthing, a number of vents were seen to be directly under fallen trees. Infrared sensors do not see through cooler objects in the foreground. The user of the data product should understand that failure to detect some heat sources is to be expected.

For the measurements at Cougar Mountain Park, Fireball worked to minimize the issues noted above in several ways. First, we attempted to fly over our calibration targets at close to the same altitude that we flew the survey. In that calibration exercise we made certain that the calibration targets where large enough to have a number of un-mixed pixels. Second, we made certain the area was imaged from several different angles so that obscuration issues were minimized even though they were certainly not eliminated. Third, we "ground-truthed" the temperature data by both thermocouple and radiative sensor measurements at representative vents/heat sources. From that effort we are comfortable that our data product is a satisfactory representation of conditions in the field. Fourth, we caution the customer that our data product may somewhat underestimate the highest temperatures that may exist in the field. We would suggest that viewing the data products with attention to area in combination with elevated temperature is probably more appropriate than simply focusing on the highest temperature as a measure of the intensity and extent of the underground fire.

Calibration of the IR Camera with External Temperature Sources

Water baths of different temperatures are useful sources of external temperature signatures for use in calibration of infrared sensors. Water has an emissivity 0.97, has a high specific heat so that it changes temperature relatively slowly, and is easily heated, transported, and mixed.

For the measurements at Cougar Mountain plastic tubs of water at that started at five different temperatures where set out in Nike Park. Cromel-Constantan thermocouple were placed in each of the tubs as well as in the damp grass adjacent to the tubs. The thermocouple voltages were read and recorded as degrees Celsius by a Campbell Scientific, Inc. (Logan, Utah) Model CR-10 data logger.

The tubs of water were placed on a piece of Styrofoam insulation board to reduce heat transfer to the ground. Since heating and cooling were not provided the water above ambient temperature cooled toward ambient while water below ambient temperature warmed toward ambient once the ice that we place in the water melted. The idea was to pass over the temperature sources several times during the flight operation and thereby collecting pixel values at a range of temperatures.

During the flight operation two different camera settings where used. The first setting could accommodate temperatures up to 50 C without saturation but could not detect small low temperature targets well. After examining the designated area at that camera setting and finding no targets at such high temperatures the camera was set to detect lower temperature targets. As the figure and table below indicate, pixel values at that lower camera setting and temperatures were correlated at minutes 71 and 113 into the data logger record.

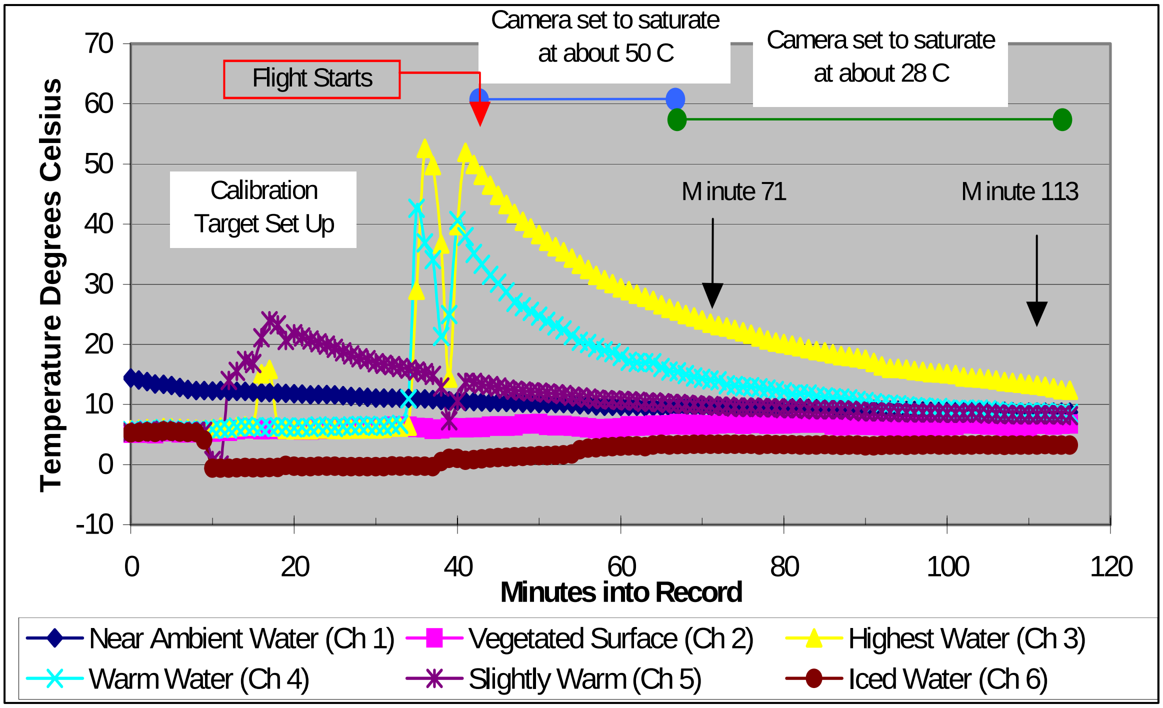


Figure A-2. Temperature Calibrating Water Targets

Table A-1 – Temperature Calibrating Water Target Data Logger Data

	Data Logger/Water Bath Number					
	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6
Minute 71 Target Temperatures	9.47	6.628	23.54	14.08	9.8	3.357
Original Pixel Value	159	146	221	179	160	132
Contrast Stretched Pixel Value (rescaled for better resolution)	41	23	210	88	44	0
Minute 113 Target Temperatures	8.7	6.579	12.77	8.51	8.28	3.245
Original Pixel Value	155	145	174	154	153	130
Contrast Stretched Pixel Value (rescaled for better resolution)	39	26	72	36	32	0

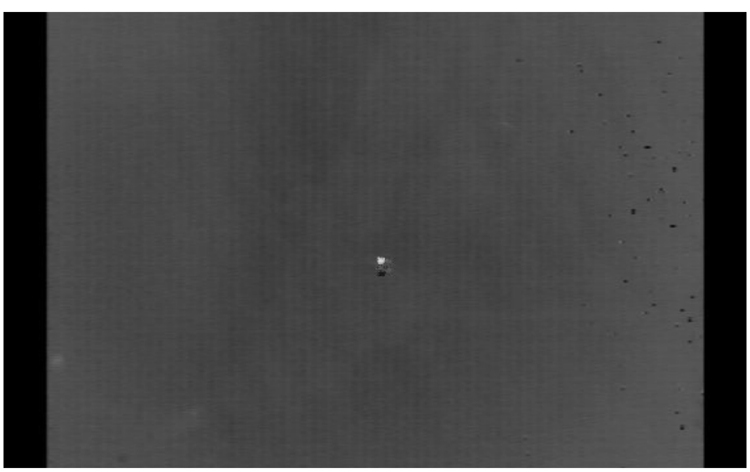


Figure A-3. IR camera frame from the Minute 71 pass over the calibration targets.

<u>Fireball IR System Description and Intended Use at Cougar Mountain Park</u>

Introduction

The Fireball system is a "purpose built" that focuses on the ability to automatically and correctly extract information from thermal and visual images and put that information "on the map in real time." There are two reasons that putting the information (or its parent imagery) on the map in real time is important. First, the operator can make certain that the system is characterizing conditions well (real-time feedback). Second, our most common clients are emergency incident managers who need the information in near real-time.

The imaging portion of the Fireball System is a Wescam 12 inch, Dual Sensor 3-axis gyro-stabilized gimbal. The thermal imager in this system is a 256 x 256 8-bit Indium-Antimonide (InSb) starring array made by Cincinnati Electronics. This system is the smaller relative (one fewer sensors) of the standard EO-IR turret on the Predator Unmanned Aerial Vehicle.

The Position Resolving portion of the Fireball System is a proprietary system. It uses a Kalman Filter to unify GPS, Inertial, and other inputs to yield position that is far more accurate then any single system can provide alone.

The image processing and mapping portion of the system can ingest geographic data in industry standard formats for use as base data layers. Using position, camera, and topographic information the system projects images to the surface. From that point it is possible to extract size, shape, contiguousness, as well as pixel value information. It is possible to use these characteristics for a variety of analyses. Results of the analyses can be displayed using raster, vector or a combination of these formats. The small size of vector files makes it practical to send real time data directly from the aircraft to our network of servers.

Using data sent directly from our aircraft, subscribing emergency clients receive updated electronic and hard-copy incident maps directly to local and regional dispatch centers in a matter of a few minutes.

Precautions Regarding Temperature Measurement From FLIR Imagers

As far as we are aware, all "Forward Looking Infrared" (FLIR = aircraft qualified, IR imaging systems with a video-based output) on the market today are single waveband system (either the 3-5 micron or 8 – 11 micron wavebands). It is not possible to measure temperature using a one waveband sensor unless one makes and validates significant assumptions. The required assumptions are these:

1. The temperature values to be measured are within roughly +/- 50 Degrees K of the calibration blackbody

2. Pixels are of un-mixed temperature and emissivity. Otherwise (i.e. normally) one gets a value portraying an undefined central tendency between objects composing the pixel.
3. Atmospheric corrections are made, primarily water vapor content and atomized water content (clouds/fog).
4. Emissivities are known and uniform within a pixel.
5. Distance from source to imaging system known.

With respect to very hot targets (such as fire) there can be a camera saturation (bloom) problem. Cameras have linear scales of typically 8-bit (some now 10 bit) range. Meanwhile the quantity of thermal energy emitted by objects is a function of the 4th power of their temperature. Thus, it is not hard to see that one could have a problem if they tried to both keep the background and the burning object in an 8-bit range.

<u>Summary of How the Fireball System Was Used in Cougar Mountain Park</u>.

- Image Capture
  - Both the IR and visible-wavelength images originate from imagers that put out NTSC video.
  - NTSC (8 bit analog) frames from both video streams are digitized to jpeg format at user specified intervals under computer control.
  - All NTSC frames are (optionally) also recorded to tape.

- Navigation/Position
  - A high precision, high accuracy aircraft position solution is derived at a frequency of 5 Hz from a fusion of solutions provided by high quality GPS and inertial navigation devices.

- Fusion of Navigation and Image Data for Storage
  - Aircraft and camera position data are capture synchronously with image data.
  - Image and position data are stored in a database structure.

- Image Processing
  - Image and position data as well as underlying topographic and feature information are used to geo-reference and ortho-rectify images.
  - Image geo-referencing/ortho-rectifying can be done in real time or from data stored in the database after landing.
  - Once referenced, images are processed to extract information on position and characteristics of areas of different color, brightness, patterns and so forth.
  - Geographic centers of extracted image features are calculated and icons representing different conditions are assigned to those coordinates and attributes are added to industry standard shapefiles (a vector data format).

- Raster Mosaics.
    - Geo processing of multiple sequential images yields a mosaic of raster images.
    - Flights are planned so that there is at least 20% overlap with images in parallel flight lines.
    - Image capture rates are set so that all areas of the surface appear in at least 2 images (2X over sampling) providing two look angles through plant canopies as well as redundant images. The capture rate is actually set high enough to yield at about 10% overlap with adjacent images (allowing feature-matching mosaics) when every second image is sorted into a second data set. By comparison features identifiable in the two resultant raster mosaics one can gain considerable confidence in the geo-location of features.
    - Holes in the LIDAR data suggest that some areas in Cougar Mtn. Park have particularly dense canopies. The pre-operation flight planned as the helicopter arrives in the Renton area will yield good information as to any benefits that might be gained from higher rates of over sampling/additional look angles.
    - Best estimates of Thermal Patterns/Contours will be developed by joining information gathered from the different look-angles.

- Temperature Calibration and Imager Settings. A substantial idea of optimal imager gain and offset settings will be achieved in the pre-operational flight. Greatest sensitivity to temperature anomalies can be achieved by setting the IR imager so that normal background yields very low pixel values and the highest expected temperature is given a level near 256. These settings will be achieved in the first phase of the operational flight as the aircraft hovers over objects of known temperature in the Nike Site area of the park. The objects will be the ground surface, an electrically heated metal plate, and the hood of a running vehicle. Multiple thermocouples will be attached to these objects to establish their temperature. Use of three objects will establish the linear nature of the imager response.

- Ground Truthing. Real-time image processing during the operational flight will indicate the location of anomalous hot areas. A map of showing those locations will be printed in the truck. This will allows us to immediately understand the scope of what was detected. The map will then be used to guide the collection of sufficient ground truth information to vet the temperature contour product. Ground truth information will be gathered at a number of steam vents using both an Everest Model 210 infrared radiometer and a chromel-constantan thermocouple/data logger set-up.

Lessons Learned

1. Having completed one survey, we know have a solid idea of the range of temperatures likely to be seen at Cougar Mountain. With this knowledge we will set the IR camera to its medium range rather than the high range used on this flight. This will provide greater temperature separation/definition and perhaps more image detail than was achieved in this operation.
2. The target altitude for the helicopter chosen for this mission was 300 feet above ground level (AGL). This was a good compromise between image detail and ability to relate images to features on the ground. But, as stands to reason, the best thermal image information was obtained from at pass over the active area at about 100 feet AGL. It is recommended that following large-scale surveys, low level imagery be collected in active areas.
3. An aerial photograph of the Cougar Mountain area taken by AirPhoto USA was bought by Fireball before this operation. That photograph was invaluable in planning, carrying out, and processing the data.
4. As indispensable as the aerial photo that we had was, it would have been more helpful if a large scale image taken in winter had been available. It had been our plan to take such a picture with the system on the helicopter but a low cloud ceiling made that impossible. Trying to save money I did not take advantage of clearer skies the next morning to go back and photograph the park from 5,000 feet AGL as originally planned. That was short-sighted, as having a leaf-off image as a geo-referencing aid would have sped the correlation of our visible imagery with ground features. That correlation became more important than expected because of a problem that occurred with our automatic geo-referencing system.
5. Our automatic geo-referencing system did not function properly. That system is based on a Kalman Filter, which varies the dependence of the navigation solution among states determines by the GPS and the Inertial Navigation Solution based on variance in those states. Numerous subsequent tests of the system have not produced another failure of the filter. Failure of the automatic system made manual correction of the geo-referencing necessary.
6. One important means of checking image geo-referencing is to use known “control points” marked and made visible before the flight. The actual locations of those points are determined by time-averaged GPS readings. In some cases, our GPS reading at control points were too noisy to use. This was caused by degradation of the GPS signal by the trees and their canopies. Use of a pole to elevate the GPS antenna even 10 to 15 feet off the ground would have been quite helpful.